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NET ENERGY EFFECTS AND RESOURCE DEPLETION: AN ALL-OIL ECONOMY

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ABSTRACT

The impact of net energy effects on resource lifetimes was examined for the hypothetical case of the U.S. economic system consuming crude petroleum as its only energy resource. Results indicate that net energy effects do not result in significant excess energy use until resources become quite difficult to extract. Prior to the point at which synthetic oil from coal would become economically attractive, net energy effects are not particularly severe. Beyond that point (e.g., if synfuels were not available), net energy effects become quite severe; in their absence the resource would have lasted 70% longer. In fact, the energy required to obtain energy steadily increases to a point where the net energy yield equals zero, before all the resources are recovered.

ACKNOWLEDGEMENT

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1.0 INTRODUCTION

In recent years there has been widespread concern about the natural energy yield of various energy supply facilities. Net energy analyses have been performed for both fossil and nuclear energy systems, taking into account the direct and indirect energy required to produce a unit of refined fuel or electricity. Direct energy requirements refer to energy used in the extraction and refining sectors of the economy, while indirect energy is that consumed in other sectors of the economy to provide the goods and services needed by the energy extraction and refining sectors of the economy. The methodology for performing such calculations was outlined by Bullard (1976), and has been employed by Pilati (1977), Development Sciences Inc. (1977), and the Colorado Energy Research Institute (1976).

All of the analyses cited above were static; they considered a steady state operation of energy facilities under assumptions of fixed technology and fixed quality of the resource input. Our purpose here is to examine the impact over time as a resource is depleted and requires increasing inputs to produce a unit of output. In this report we focus on oil extraction, starting with conventional onshore drilling technology and proceeding through offshore, secondary and tertiary recovery techniques. For purposes of analysis we construct a hypothetical single fuel economy, assuming the entire U.S. economy depends solely on crude petroleum for its energy supply. This assumption enables us to remove the "distortions" in conventional analyses caused by other resources with higher net energy yields "subsidizing" oil extraction technology. In the conventional framework, it is difficult to determine the extent to which one technology subsidizes another, while the analytical construct of a single-fuel economy allows us to examine individually the net energy yield of each technology.

Another closely related issue is also examined in this report. Traditional estimates of United States energy resource reserves are obtained by simply adding the resources of various fuel types to obtain total reserve estimates. A potential problem with this approach is that the estimates of coal reserves, for example, do not include a debit for the petroleum needed to extract it. Such reserve estimates are gross rather than net, and therefore overstate the usable recoverable quantity. By examining each resource individually using our single-fuel economy assumption, it is possible to compare total resource lifetimes with and without the net energy effect. In this report, we analyze the situation for U.S. oil reserves.

Section 2 describes the methodology for constructing the single-fuel economy model and for modifying the conventional representation to include net energy effects. Results and conclusions are presented in section 3, while modeling and data details are presented in the appendices.

2.0 METHODOLOGY

2.1 Models Employed

In this section we modify existing CAC models and data bases to allow computing projected energy costs of crude oil production in the future. A comprehensive description of current (1967) crude oil technology is already embodied in the CAC energy input-output model.[1] This model has been used to compute both the direct and total energy requirements of 1967 crude oil production. Examination of these figures reveal a direct energy require-

[1] This model is described in Herendeen and Bullard (1975), Bullard and Herendeen (1975), and Knecht and Bullard (1975). We are using the latter version at a 40-sector level of aggregation (12 energy sources, 8 energy services, and 20 nonenergy sectors.)

ment of 1.024 Btu crude oil per Btu produced *at the wellhead*.[2] In addition to the 1.0 Btu of oil actually delivered, this figure includes .0019 Btu/ Btu of other forms of energy consumed by crude oil producers themselves for pumping, flaring, heating, lighting and other energy uses.

In 1967 the *total* energy cost of crude oil production was 1.0568 Btu/ Btu.[3] This figure includes all of the direct energy plus the energy consumed to make the goods and services used by the oil industry in 1967. The crude oil industry consumed this indirect energy in the form of chemicals, business services, maintenance services, transportation, and many other goods and services. Because capital costs are by convention considered part of final demand, this total energy figure does not include the energy cost of the industry's capital investments in 1967.

2.2 Representing the All-Oil Economy

The CAC input-output model used in this report contains 12 energy supplies (e.g. coal, nuclear electricity, and utility gas) and eight energy products (e.g. feedstock, space heat, and industrial process heat). In a hypothetical all-oil economy, these same energy services would be provided entirely by crude oil in one of three forms: as crude oil, refined oil, or electricity generated from refined oil. In the usual model, the technology and energy costs of delivering energy forms is shown by a technology matrix $\underline{\underline{A}}$ with each coefficient A_{ij} equal to the input of type i needed to produce one Btu of energy service of type j. For example A(coal, coke feedstocks) = 1.49 or 1.49 Btu of coal is required to produce one Btu coke for use as a feedstock. In our hypothetical economy, all such coefficients were

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[2] Direct energy data are found in Simpson and Smith (1974), p. 33.

[3] Herendeen and Bullard (1975), p. 32.

adjusted from a 1985 baseline,* substituting refined oil for natural gas and coal. Electrical end-uses of energy were unchanged, except that the electricity was all generated from oil. Appendix A explains in detail the assumptions and calculations necessary to convert the entire energy submatrix of $\underline{\underline{A}}$ to an all-oil scenario.

2.3 Operating and Capital Requirements for Crude Oil Production

The 1967 model provides a detailed characterization of current crude oil technology and costs via two key vectors of coefficients: the operation of the crude oil industry as described by the direct requirements column for crude oil ($A_{i,crude}$) and the vector of oil industry capital investments. These parameters are expected to change over time due to many economic conditions: improved technology, increasingly scarce oil reserves, progressively less accessible oil extraction, increased labor and investment costs, and a number of other factors.

There are many different ways to examine the projected growth of crude oil costs. We chose to examine three important indicators: *total exploration and development* (or capital) *cost per barrel, total operating cost per barrel,* and *direct energy cost per barrel.* These indicators are expressed in constant dollars and represent actual increases in physical requirements -- energy, goods and services -- needed to produce oil. Based on National Petroleum Council data, (NPC, 1972, 1973, and 1976), we have derived two real cost indices as functions of cumulative resource depletion. In this report total available domestic oil resources are assumed to be 2300 quads, an optimistic but reasonable figure.** We call the two cost indices derived OP and

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* efficiencies cited from Pilati (1976).

** Current estimates such as those by Hubbert (1974) and the U.S. Department of Interior (1976) place domestic oil reserves at approximately 1100 quads, not including an estimated 50 quads domestic oil consumption since 1967.

CAP where:

OP(c.p.) = index of real total operating requirements (million real dollars/ quad) as a function of cumulative production level (quads); OP(1967 cumulative production) = 1.00.

CAP(c.p.)= index of total capital requirements (million real dollar/ quad) as a function of cumulative depletion level (quads); CAP(1967 cumulative production) = 1.00.

In addition, we used another function based on current research concerning all-tertiary recovery to account for the crude oil industry's increasing direct energy use due to more difficult extraction. This function, called EOP, has the form:

EOP(c.p.)= index of direct energy use by the crude oil industry for oil recovery per Btu gross crude oil output; EOP(1967 cumulative production) = 1.0

The data source and statistical procedures used to generate these functions are explained in Appendix B. A graph of the functions is presented as Figure 2.

2.4 Dynamic Simulation of Resource Depletion

Figure 1 shows the conventional CAC energy input-output model, modified to allow for an iterative, dynamic calculation of GNP, crude oil consumption and costs, and other economic parameters. The model is driven by a GNP vector Y which grows at annual percentage rate r with the year index t. In our calculations, we set r = 3% and hold constant the mix of goods and services making up the GNP. The increased oil industry capital requirements needed for year t (calculated at the right of figure 1) are fed back as parallel inputs. Thus the economy must produce the "nominal" growing market basket of goods and services, plus the incremental capital equipment to discover and

develop ever-scarcer oil resources.

In the second box from left on Figure 1 the annual GNP vector is multiplied by the Leontief inverse (or total requirements) matrix, yielding the vector of total goods and services required throughout the economy to produce this GNP. This is the gross domestic output (GDO) vector; its elements are $\underline{X}_j$, where j denotes the sector of the economy considered. Proceeding to the right, the next step is to extract X_{crude} for year t from the GDO vector to find the total crude oil production required in year t. This production must be added to the previous cumulative production to get the new cumulative production (C.P.).

The new figure for C.P. is first used in the operating cost function OP[C.P.] and in the energy operating cost function EOP[C.P.] (upper right-most box). The result of this computation is a new operating-cost-per-barrel factor which is used (next box to left) to scale the current technology (or operating requirements) vector $\underline{A}_{i,crude}$ for year t. More precisely, the crude column of $\underline{\underline{A}}$ is updated by multiplying the $A_{crude,crude}$ element by EOP, to reflect specific increases in the crude direct requirements of crude, and by multiplying the rest of the crude column of $\underline{\underline{A}}$ by OP to reflect lesser increases in the crude sector's direct requirements from other sectors. This yields a new vector (proportional to the base year vector) which reflects the increasing costs of oil production occuring at the new level of cumulative production due to lower oil concentrations, deeper wells, increased chemical and energy costs, etc.

The next step (upper left) is to insert the newly computed technology vector $\underline{A}_{i,crude}$ into the technology matrix $\underline{\underline{A}}$. Then $(\underline{\underline{I}}-\underline{\underline{A}})$ must be reinverted to obtain the new total requirements matrix. Note that since this new matrix

now reflects the next year's crude oil technology (because $\underline{A}_{i,crude}$ has been scaled up), t is incremented here to t+1. Now the model is ready to accept the GNP vector $\underline{Y}(t+1)$, and multiply it by the new total requirements matrix $(\underline{\underline{I}}-\underline{\underline{A}})^{-1}$ to get the next (year t+1) total crude oil production and repeat the cycle.*

While these steps are repeated, the new cumulative production figure C.P. is also inserted into the function CAP[C.P.] to get a scale factor for the existing crude oil capital vector $\underline{C}_{i,crude}$. The vector is then multiplied by this factor, increasing the magnitude but preserving the proportions of $\underline{C}_{i,crude}$. This process yields the new crude oil capital investment vector $\underline{C}$ for year t+1. Also calculated here is the vector of increased refinery capital requirements ($\underline{R}$ for year t+1)reflecting the additional refining capacity required in an all-oil economy. Derivation of these vectors is explained in Appendix C. These two capital vectors are added to the nominal final demand vector (growing at annual rate r), and the new total final demand vector (lower left-hand box) is fed back to obtain the gross domestic output vector $\underline{X}$ for year t+1.

For each yearly iteration of the program a special subroutine examines several net energy aspects of the economy. This "net energy" subroutine begins (upper most righthand box) with the newly updated (year t+1) crude oil industry column of the $\underline{\underline{A}}$ (direct requirements) matrix. At this point, the subroutine sets the crude industry's self use of crude (element A_{11}) to zero. This has the effect of subtracting crude industry self-use from its gross output, creating a new value of *net* crude oil industry output for year t. Because all elements in the crude column of $\underline{\underline{A}}$ were formerly defined per Btu

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* Due to the approximate nature of the results sought, we do not attempt to eliminate the lag effect associated with each year's capital and operating vectors being calculated from the previous year's cumulative production. Quantitatively, the effect can be shown to be negligible.

of gross output, these must be normalized on the new net basis. This new column of $\underline{\underline{A}}$ is inserted into the modified all-oil economy $\underline{\underline{A}}$ matrix described in Appendix A, and a new Leontief inverse matrix is formed.

The first row of this Leontief inverse matrix represents the *net* crude oil energy intensities of all goods and services in the economy. We are particularly interested in examining the net energy intensity of crude oil, which represents the total indirect energy embodied in the goods and services required from all other sectors of the economy (plus the one Btu of heat content of oil) per net Btu of crude oil produced. When the value of this energy intensity becomes 2.0 Btu/Btu or greater, the extraction of oil has become a net energy loss. This is because at least one Btu equivalent of goods and services from the economy is required to extract one Btu of crude oil from the earth. At this point the economy becomes physically and economically *infeasible,* and the simulation program is terminated. The net energy subroutine also examines several other important aspects of the economy which are discussed in section 3.0.

3.0 RESULTS AND CONCLUSIONS

Figure 3 shows the growth path of the hypothetical all-oil economy over time. It also shows the energy use in an economy with constant 3% growth in GNP and no net energy effects (i.e. no increase in the energy cost of energy). The figure shows the economy running out of oil before the end of the eleventh year. But due to net energy effects, more than 17% of reserves are not physically recoverable, so the effective life of the resource is less than 10 years. Note that without net energy effects oil supplies to the lower path on Fig. 3 would last seven more years, 70% longer.

Table 1 lists the changes in several key parameters of the all-oil economy over time. Much of the growth in energy use is due to the direct energy required by the oil industry itself, which increases from 6.4 quads (9% of total energy use) in year 1 to 120 quads (35% of total energy use) in year 10.* The dollar cost of all oil industry investments rises from 1.2% to 26.8% of GNP, a factor of 22. Thus it is seen that extracting the last oil reserves requires physical resource inputs far above current levels.

It is instructive to examine the qualitative aspects of the wide gap between the all-oil and conventional growth paths in Figure 3. The major effect is summarized in the growth of $\varepsilon'-1$, the energy embodied in goods and services needed from the economic system to obtain 1 Btu net output from the crude oil sector. In year 1 ($\varepsilon'-1$) is .03 (Figure 4), indicating that every net Btu of crude oil produced required .03 Btu embodied in goods and services. By the end of year 10, ($\varepsilon'-1$) grows larger than 1.0, indicating that every net Btu of oil produced requires more than 1 Btu of goods and services from the

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* The oil industry's use of energy is defined as the sum of the crude oil industry's use of crude oil and the refinery industry's use of refined oil. Table 1 shows the <u>incremental</u> oil requirements, over and above the amount that otherwise would be required in the absence of net energy effects.

(Year)	Cumulative Production (Quads)	Annual Total Primary Energy (Quads)	Incremental Energy Consumed by Oil Industry (Percentage of Total Primary Energy)		Oil Industry Investments (% of GNP)	Net Energy Cost of Energy ($\varepsilon'-1$)
			Operating	Capital		
1	709	71.9	0.0	1.8	1.4	.032
2	783	74.9	.4	1.8	1.8	.032
3	862	78.6	1.6	2.4	2.0	.033
4	944	82.3	2.9	2.6	2.3	.033
5	1031	86.4	4.3	3.0	2.9	.034
6	1125	94.5	9.0	3.8	5.1	.075
7	1234	108.3	15.1	6.5	8.8	.143
8	1368	134.8	24.5	10.6	13.2	.263
9	1556	188.0	36.9	15.1	19.2	.496
10	1900	343.9	52.4	20.6	31.2	1.188

Table 1: Characteristics of Growth In An All-Oil Economy

economy. Hence, there is no net energy to be gained by further extraction of oil from the earth.

Let us consider several key points in the progression of the all-oil economy. During the seventh year, cumulative depletion exceeds 1170 quads, the point at which oil price reaches \$20/Bbl. in 1970 dollars. This is the price at which synthetic fuels could become economically attractive and could begin substituting for crude oil. Annual energy use at this point is 108.3 quads, while the total energy cost of energy is ε = 1.4 Btu/Btu, and about 17% of all energy (18.3 quads) is consumed by the oil industry. This contrasts to oil industry use of only 9% of all energy in the first year. Of the 18.3 quads consumed directly by the oil industry in the seventh year about 0.5 quad is required for the increased investment in larger recovery and processing structures while the remaining 17.8 quads are needed for operating deeper wells and more complex recovery technologies. When this "synfuel feasibility" point is reached, oil industry investments represent about 7.5% of GNP. In effect, real GNP must be 7.5 - 1.2 = 6.3% higher to provide the same services as a corresponding fixed-technology economy where only 1.2% of GNP is needed for energy sector investment. Moreover, the entire oil industry requires a significant portion of the output of many prominent industries for its functioning: 11% of all chemicals, 15% of stone and clay products, 22% of primary iron and steel, 12% of industrial equipment, 10% of services and over 24% of all water transport.

If in this seventh year the economic system switched to coal liquefaction technologies, the energy cost of goods and services would take a significant jump (Figure 3). This is due to the fact that the total energy cost of this synthetic fuel is about 1.6 Btu/Btu, 0.2 Btu/Btu more than crude oil at that point. All energy used in the single fuel economy would become more energy-

intensive and total system energy use would increase by about 22 quads. In reality, coal liquefaction is the "backstop technology" that would essentially prevent further extraction of liquid petroleum resources. To demonstrate what would have happened in the absence of such a backstop technology, we carried the solution to the point where net energy effects prevent complete resource exhaustion.

In the tenth year the energy-economic system becomes infeasible in the sense that more than one Btu embodied in goods and services is required to extract one net Btu of crude oil from the earth. At this time, oil price is about $100/Bbl and total annual energy use is 344 quads, 35% which is consumed by the oil industry. The crude oil industry directly consumes 29% of its own output while the refined oil industry uses 9% of its end product. The oil industry also consumes very large percentages of major industrial outputs: 26% of construction, 32% of chemicals, 42% of stone and clay products, 45% of primary iron and steel, 37% of industrial equipment, 40% of all water transportation and over 43% of all services. Finally, oil industry investments account for 26.8% of real GNP. In other words, GNP (since it includes investment) would have to rise by that amount over the nominal 3% growth path to provide the same services as an economy with no net energy effects.

In reality, the backstop technology (liquefied coal) would take over long before the economy reached the point of infeasibility. At the point where synfuel use becomes feasible there are no devastating net energy effects in the all-oil economy. Moreover, cumulative depletion is essentially the same until the seventh year for both of the growth curves in Figure 3.* These

* Thus net energy affects do not significantly alter the time at which synfuels will become economically competitive.

conclusions are based on actual NPC data and so are expected to be quantitatively valid.

Net energy effects do become significant after the seventh year, causing several important changes in the economy. Energy intensities increase rapidly, yielding a rapid exponential increase in total energy use despite only modest increases in final demand. Because so much energy must be used simply to get more energy, total resource lifetime is decreased from 17 years to 10, a 44% decrease due entirely to net energy effects. This conclusion is based on our linear extrapolation of NPC projections and so can have only qualitative significance. However, in view of the nonlinear nature of extraction cost increases, our linear extrapolation would appear to be conservative. If the cost increases are in fact nonlinear, the economic effects of developing oil resources to the point of complete exhaustion could be far more severe than indicated in this report.

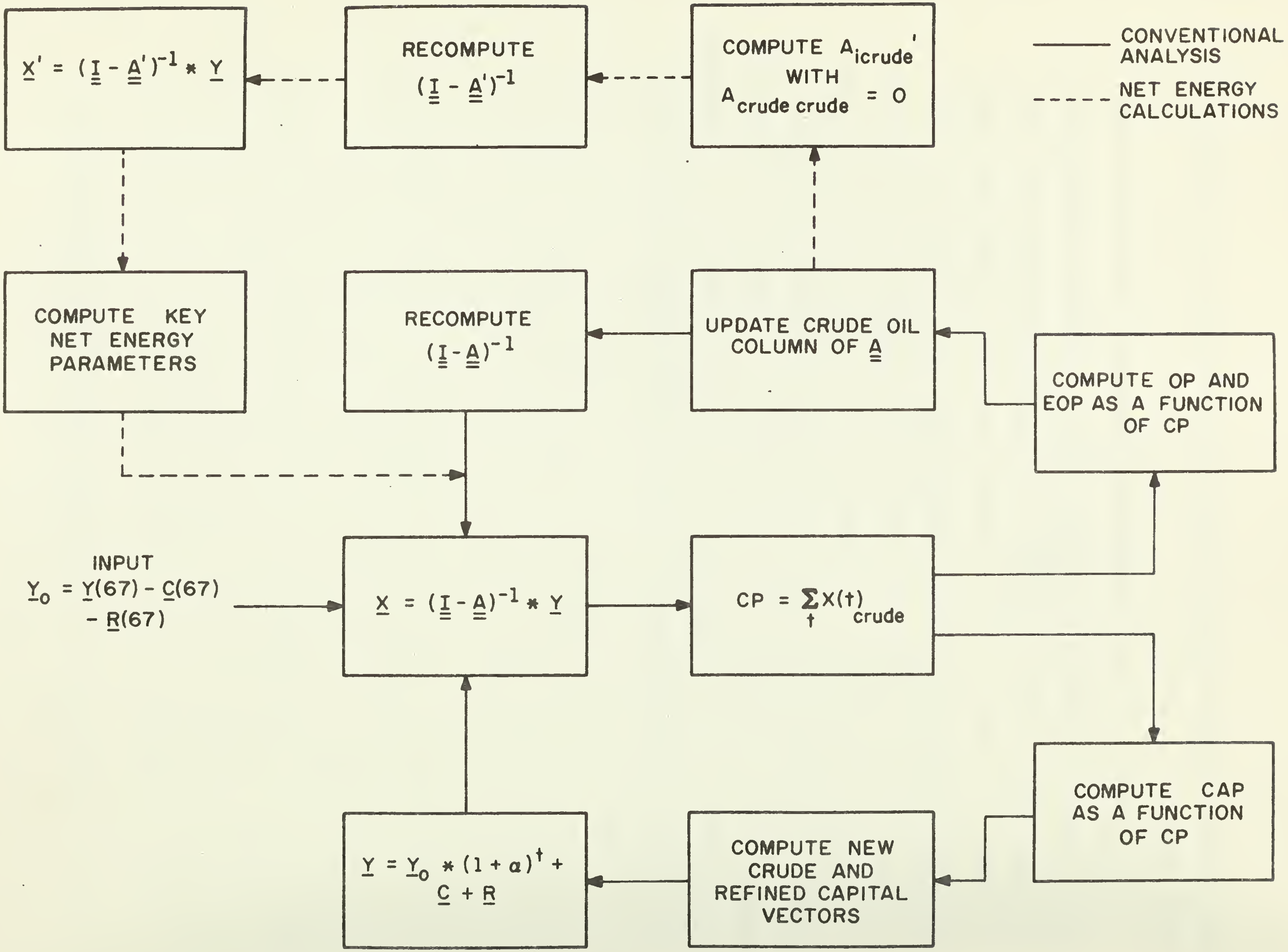

FIGURE 1: FLOW DIAGRAM FOR SIMULATION OF AN ALL-OIL ECONOMY

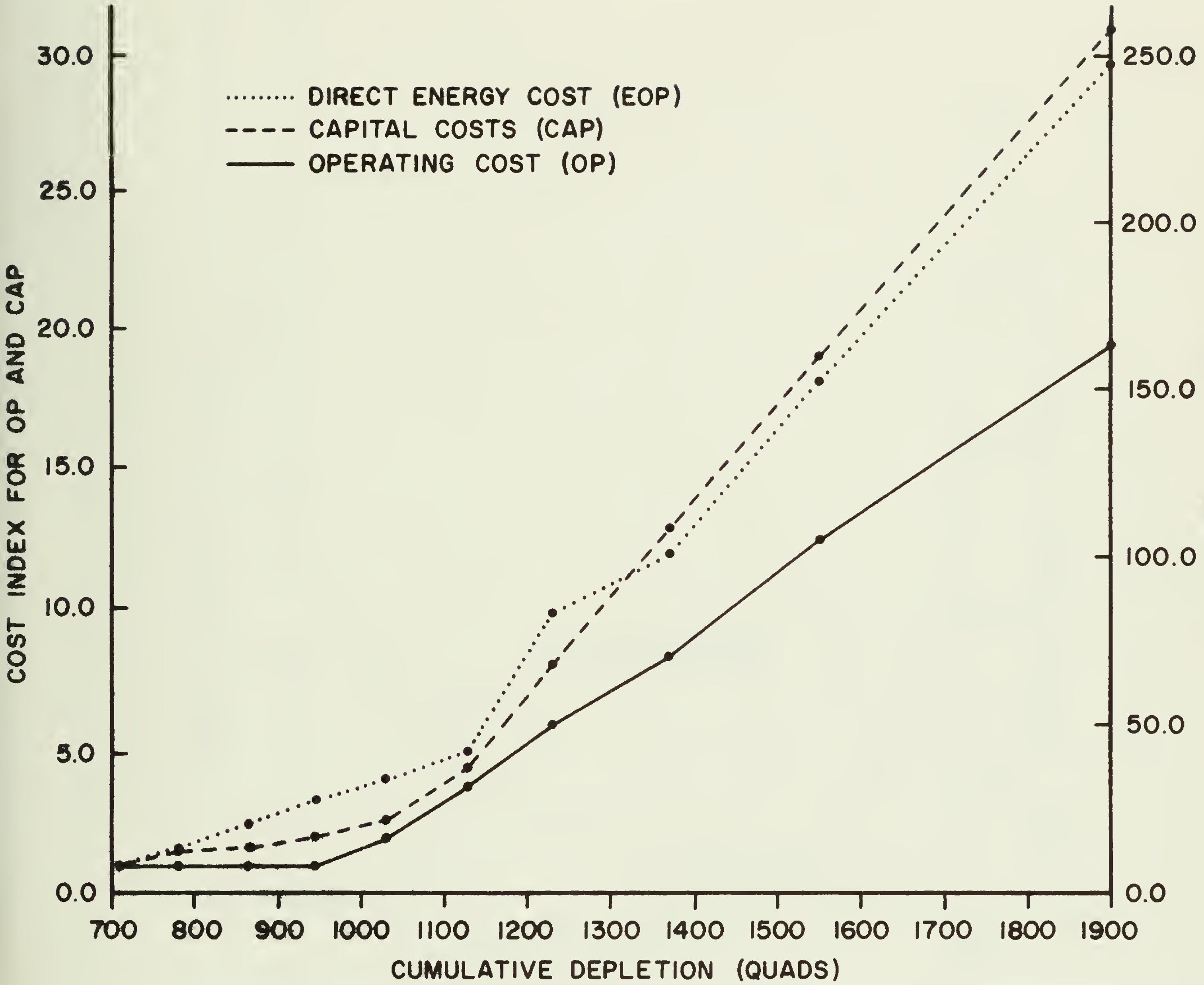

FIGURE 2: OPERATING, CAPITAL, AND DIRECT ENERGY COST INDEX FUNCTIONS

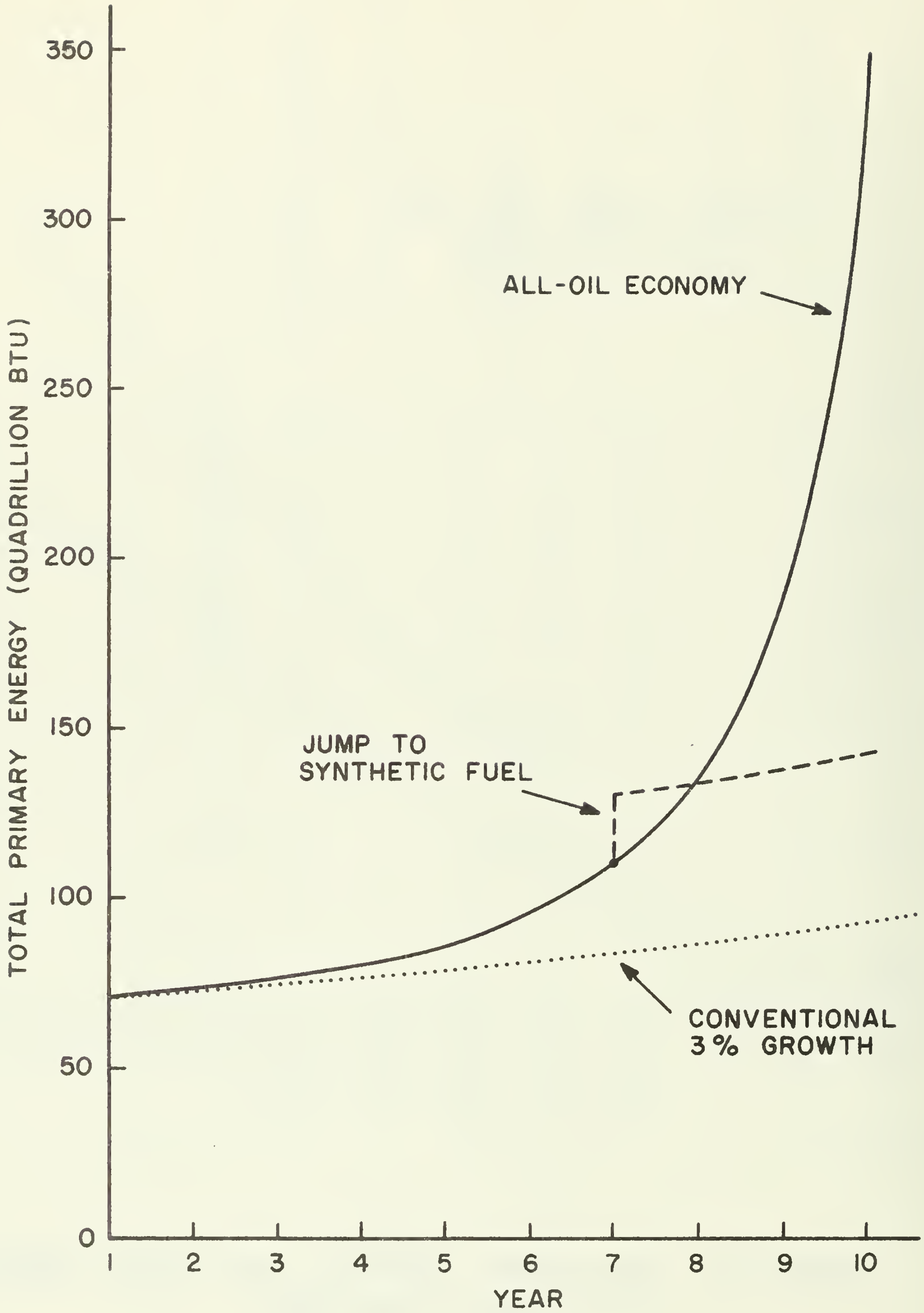

FIGURE 3: ENERGY GROWTH IN ALL-OIL ECONOMY WITH SYNTHETIC FUELS AS "BACKSTOP" TECHNOLOGY

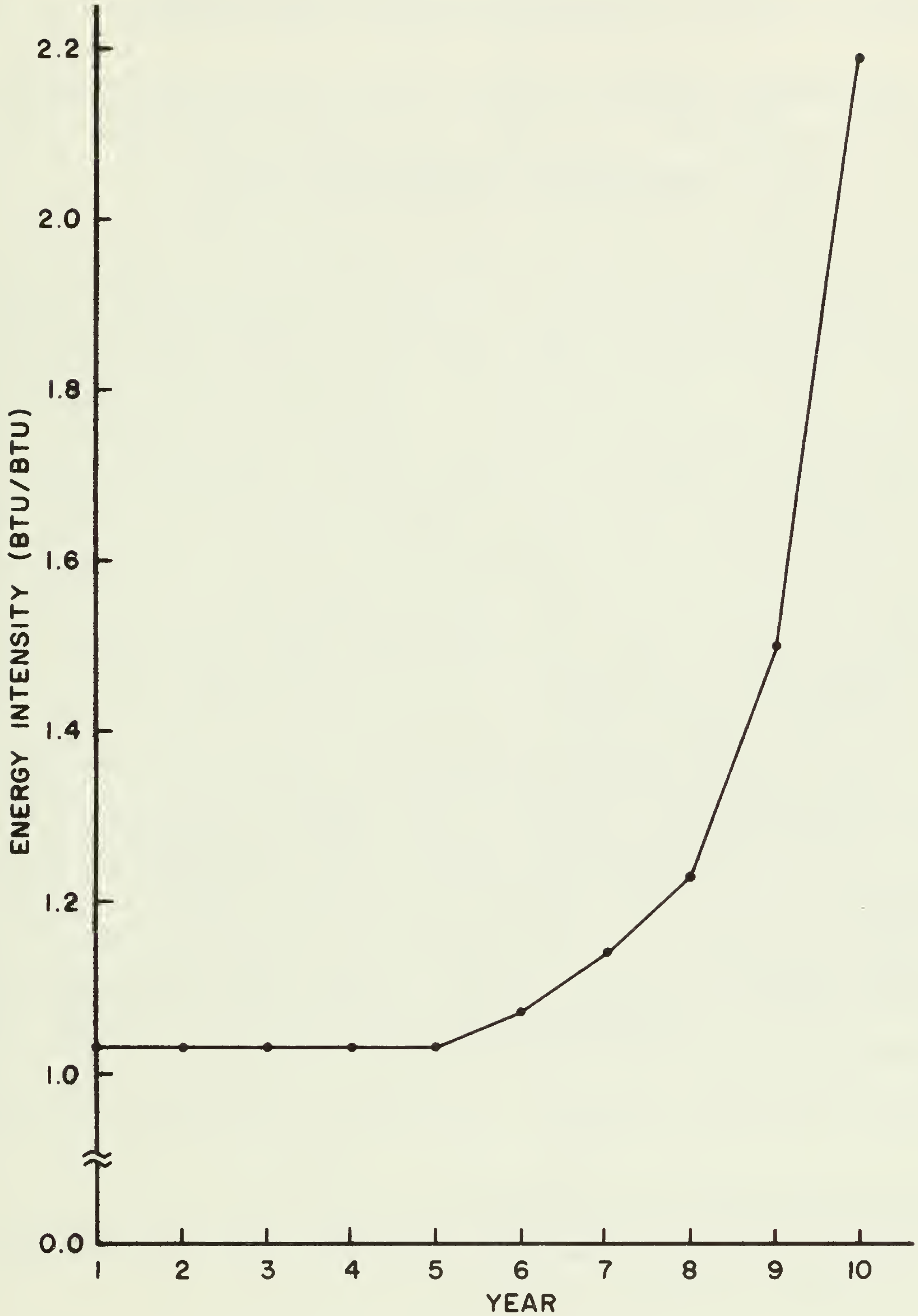

FIGURE 4: ENERGY COST OF ONE NET BTU OF CRUDE OIL IN ALL-OIL ECONOMY

Appendix A - Energy Products Matrix for an All-Oil Economy

This Appendix explains the changes in the CAC 40-sector energy input-output model required to create the hypothetical situation where only one source of energy -- crude oil -- is available to the economy. Because every product made from or with other energy sources has a substitute, this "all-oil" scenario does not require any changes in either magnitude or composition of final demand. Moreover, these substitute products and processes occur (with one minor exception)* within existing full-scale industries. Thus the problem reduces to shifting the energy products now generated by coal, natural gas, nuclear electric and renewable electric energy sources to those made with crude oil, refined oil, and oil-burning energy sources. All energy products requiring electricity must be delivered from fossil electric, and feedstocks and fuels must use petroleum.

Energy products delivered from different sources are in general delivered with different efficiencies. For example, delivering one Btu of actual water heat from refined petroleum requires $(\frac{(1\ \text{Btu})}{.63}) \cong 1.53$ Btu of refined petroleum where (.63) represents the end-use efficiency (of the oil water heater). Similarly one Btu of actual water heat from a utility gas requires (1 Btu/.61) $\cong$ 1.54 Btu gas where .61 represents the end use efficiency. Shifting all water heat to refined petroleum means

* No substitute process now exists for creating coke feedstocks from crude oil. We have assumed such a process to exist at the same overall energy efficiency.

that the total actual water heat energy required is:

$$\left(\begin{matrix}\text{former energy required from}\\ \text{refined petroleum}\end{matrix}\right) + \left[\left(\begin{matrix}\text{former energy required from}\\ \text{natural gas}\end{matrix}\right) * \left(\frac{\text{end use efficiency of natural gas}}{\text{end use efficiency of refined petroleum}}\right)\right]$$

The last factor insures that the new energy requirement listed as coming entirely from crude oil could in fact provide the needed amount of actual process water heat using current technologies.

A computation similar to the above example is required for every coefficient change in the attached submatrix. Every one of these changes is explained explicitly in the notes following the table. All end-use efficiencies are taken from ERDA Report Number 48 (1975). One minor difference from the above example applying to all calculations is that everything is done *per Btu finally delivered energy product*. Also, due to a large decrease in the efficiency of residential space heating and increased self-use in the oil refining sector, total energy use in the all-oil economy in 1967 is approximately 20 quads larger than total energy use in the real 1967 economy. Neither of these effects change any of the principles behind -- or results of -- these calculations.

TABLE A

1967 INITIALIZATION ENERGY SOURCE AND PRODUCT SUBMATRIX FOR A HYPOTHETICAL ALL-CRUDE ECONOMY

	1 Coal	2 Crude	3 Shale	4 Coal Gas	5 S. R. C.	6 Ref. Pet.	7 Gas U.	8 CCC	9 Fossil Elec.	10 LWR	11 HTGR	12 Renew Elec.	13 Coke F.S.	14 Chem. F.S.	15 Motive Power	16 Proc. Heat	17 Water Heat	18 Space Heat	19 Air Cond. (A/C)	20 Elec. Power
Coal A	.03 0.0	- -				- -	- -		1.5567 0.0	- -		- -	1.49261 0.0	.03877 0.0	- -	.2328 0.0	- -	- -	- -	- -
Crude B	- -	.02095 .00187*				1.0 1.0*	1.0 0.0		- -	- -		- -	0.0 1.49261	0.0 0.0	- -	- -	- -	- -	- -	- -
Shale Oil C	- -	- -				- -	- -		- -	- -		- -	- -	- -	- -	- -	- -	- -	- -	- -
Coal Gas D	- -	- -				- -	- -		- -	- -		- -	- -	- -	- -	- -	- -	- -	- -	- -
S. R. C. E	- -	- -				- -	- -		- -	- -		- -	- -	- -	- -	- -	- -	- -	- -	- -
Ref. Pet F	- -	- -				.09 .09*	- -		.7602 2.955	- -		- -	- -	.7367 1.0*	5.0 5.0	.1976 1.22480	.2809 1.0[illegible]53	.6[illegible] 1.[illegible]	- -	- -
Gas U. G	- -	- -				- -	.052 0.0		.6381 0.0	- -		- -	- -	.2245 0.0	- -	.936 0.0	.7928 0.0	.5191 0.0	.01123 0.0	- -
CCC H	- -	- -				- -	- -		- -	- -		- -	- -	- -	- -	- -	- -	- -	- -	- -
Fossil Elec. I	- -	- -				- -	- -		.10 .10	- -		- -	- -	- -	- -	.02777 .04560	.2053 .33705	.0749 .12303	.18247 .30575*	.609 1.00
LWR J	- -	- -				- -	- -		- -	.10 0.0		- -	- -	- -	- -	.01272 0.0	.094 0.0	.0343 0.0	.08359 0.0	.279 0.0
HTGR H	- -	- -				- -	- -		- -	- -		- -	- -	- -	- -	- -	- -	- -	- -	- -
Renew Elec. (RN) L	- -	- -				- -	- -		- -	- -		.10 0.0	- -	- -	- -	.00511 0.0	.03775 0.0	.0138 0.0	.03356 0.0	.112 0.0

NOTE: Top number is conventional 1967 value; bottom value applies to all-oil economy. Double blanks means both entries are 0.0. See notes for explanation of all values listed referenced by row (letter) and column (number).

Notes to Table A

These notes explain all changes in Table A and are referenced by row (letter) and column (number).

1A - coal self-use eliminated since no external coal flows.
THIS ELIMINATION OF SELF-USE ALSO APPLIES TO: 7G (Gas Utilities), 10J (LWR), 12L (Renewable Electric).

2B - The crude/crude value is initialized at the 1967 value. As the all-crude scenario computer program runs it will increase the entire crude column (col. 2) at each step. Therefore this entry is really the initial value of a variable in the variable vector (col. 2). Since natural gas has been eliminated from the economy, the old self-use number does not apply. From Simpson and Smith (1974), the following values are obtained (in Btu x 10^{15}):

Sector 8.00: Crude Oil and Gas:

$$\frac{\text{total internal energy use (including oil, gas, and gas liquids}}{\text{total energy into sector}} = \frac{.99}{42.44} = .02 = \text{old coefficient}$$

Sector 8.00 without natural gas or gas liquids:

$$\frac{\text{total internal energy use}}{\text{total energy input (including imports)}} = \frac{.04}{21.36} = .00187 = \text{new coefficient}$$

6B - Crude/Refined Pet. is always 1.0 by def.

6F - Refined pet. self-use (refinery efficiency) is assumed unchanged. This is an efficiency of 91% which is the same value as 1985 refinery efficiency from ERDA Report Number 48 (1975).

7B - This eliminates the flow of natural gas co-produced in the crude oil sector.

7G - see 1A.

COLUMN 9

Fossil Electric receives per *Btu of output*, at delivery efficiencies as specified in ERDA Report Number 48 (1975).

Row	Btu received per Btu Fossil Electricity	End use efficiency	total primary energy efficiency
A	1.5567 Btu from Coal	1.00	.34
F	.7602 Btu from Ref. Pet.	1.00	.34
G	.6381 Btu from Gas Utilities	1.00	.34
I	.10 Btu self-use	1.00	.34

Because all end use efficiencies are the same the new refined petroleum coefficient is just the sum of all coefficients. Self-use remains the same.

new refined petroleum coefficient = .7602 + .6381 + 1.5567 = 2.9550 Btu/Btu

10J - see 1A

12L - see 1A

COLUMN 13

Coal provides 1.49281 Btu to produce 1 Btu feedstock. According to ERDA Report Number 48 (1975) there is no 1985 technology to provide 1 Btu of feedstock from any amount of petroleum. We assume some hypothetical process which also requires 1.5 Btu of crude oil to produce 1 Btu of feedstock..

COLUMN 14

We assume all chemical feedstock is provided by oil at 1.0 Btu/Btu.

COLUMN 16: PROCESS HEAT

Row	Btu required per Btu Process Heat	End use efficiency	Total Primary Efficiency
A	.2328 Btu coal	(.75)	.495
F	.1976 Btu Ref. Pet.	.75	.75
G	.936 Btu natural gas	.70	.70
I	.02777 Fossil Electricity	.57	.1938
J	.01272 LWR	.57	.1938
L	.00511 R.E.	.57	.1938

Because all electricity is delivered at the same efficiency, the new fossil electric coefficient is the sum of I, J and L electric uses:
.02737 + .01272 + .00511 = .04560.

The new refined petroleum coefficient is the old coefficient 0.1976.

- PLUS -

(.2328 Btu)(.495 actual delivered heat from coal)($.75^{-1}$ required for heat from ref. pet.) = .1536

- PLUS -

(.936 Btu)(.70 actual delivered heat from gas)($.75^{-1}$ required for heat from ref. pet.) = .87360

TOTAL NEW COEFFICIENT = 1.22480

COLUMN 17

Row	Btu needed per Btu Water Heat	End use Efficiency	Total Primary Efficiency
F	.2809 Btu Ref. Pet.	.63	
G	.7928 Btu Gas Utilities	.61	
I	.2053 Btu Fossil Electricity	.90	.31
J	.094 Btu LWR	.90	.31
L	.03775 Btu R.E.	.90	.31

The new fossil electricity is just the sum of the old electricity coefficients (all efficiencies same):

.2053 + .094 + .03775 = .33705

The new refined petroleum coefficient is old coefficient .2809

- PLUS -

(.7928 Gas U)(.61 eff. to get actual heat from gas)($.63^{-1}$ to get heat from ref. pet.) = .76763

TOTAL NEW COEFFICIENT = 1.04853

COLUMN 18: SPACE HEAT

The new refined petroleum coefficient is the old coefficient .93576

- PLUS -

(.77955)(.51 eff. to get actual heat from gas)($.47^{-1}$ to get heat from ref. pet.)

TOTAL NEW COEFFICIENT = .93576 + .845589 = 1.78185 Btu/Btu.

The new fossil electric coefficient is just the sum of all old coefficients = .18471 = .1125 + .05154 + .02067

COLUMN 19: AIR CONDITIONING

Row	Btu needed per Btu of Air Conditioning	Coefficient of performance
G	.01123 Btu from Gas U	1.8
I	.18247 Btu from Fossil Elec.	
J	.08359 Btu from LWR	3.3
L	.03356 Btu from R.E.	

We assume all air-conditioning is provided by fossil electricity with a coefficient of performance of 3.27. Therefore the A coefficient = (coeff. of perf.)$^{-1}$ = .30575.

COLUMN 20

New fossil electric coefficient is the sum of all electric coefficients since all electric power is delivered at the same end-use efficiency:

$$.609 + .279 + .112 = 1.00$$

Appendix B: Derivation of Operating and Capital Cost Indices for the All-Oil Economy

B1.0 INTRODUCTION

This Appendix describes data, assumptions and procedures employed to generate energy operating, general operating and capital cost index functions. These functions called EOP, OP and CAP respectively, are functions of cumulative depletion of oil (in quads), and produce a scalar value which inflates real total operating or capital costs normalized to a value of 1.0 in 1967.

Below are two sections of this Appendix. The first explains the data base used to generate the functions. The data are in the form of sets containing operating cost, capital cost, and price at one level of cumulative depletion. The second section describes the procedure used to interpolate between these points and extrapolate beyond them to an ultimate cumulative depletion of 2300 quads.

B2.0 CRUDE OIL COST DATA BASE

The first seven points in Table B1 consist of ordered sets of data in the form (level of cumulative depletion, operating cost, capital cost, and price). These data come directly from the following two reports:

(1) U.S. Energy Outlook
A Report of the Natural Petroleum Council's Committee on U.S. Energy Outlook
John G. McLean, Chairman
December 1972

(2) U.S. Energy Outlook: Oil and Gas Availability
A Report by the Oil and Gas Supply Task Groups
Lloyd E. Elkins and John Horn, Chairmen
Copyright 1973

These reports consider six possible scenarios of domestic crude oil production up to 1985 using a single demand projection. We employ data from the scenario labeled case I, characterized by highest finding rate, highest growth in drilling

rate, and highest supply. The reports address oil production in the entire United States by all types of recovery and are based on an industry return-on-investment of 10-20%. Of the first seven rows of Table B1, the first four are based on historic data from the years 1960, 1965, 1970 and 1971. The fifth, sixth and seventh points are projections to years 1975, 1980 and 1985.

The eighth and ninth data points in Table B1 consist only of price information and are from a different National Petroleum Council report, *Enhanced Oil Recovery* (Dec. 1976). In contrast to all previous results this report does not include capital and operating cost information, only price received per barrel.* We assume that enhanced oil recovery begins at a cumulative depletion level of 980 quads essentially neglecting the impact of double-counting any pre-1985 enhanced oil recovered that might have entered into both NPC reports. From the graph on page 5 of *Enhanced Oil Recovery,* we obtain two points as follows:

incremental ultimate recovery (quads)	total cumulative depletion including increment (quads)	Price per barrel ($1976)
90	1070	$15
60	1130	$25

The rightmost column of oil prices (above) is in 1976 dollars and must be deflated to 1970 dollars to be consistent with previous NPC data. This is

* In addition, NPC defines this price in an unconventional way: "For the five oil price cases, prices were assumed to be effective immediately and to remain constant through the 1976-2000 period. For example, results shown for a $20 per barrel oil price in 1970 do not mean that oil will reach a price of $20 per barrel in that year; they illustrate the potential producing rates and incremental recovery that could be achieved by EOR if oil were to be valued at $20/bbl from 1976 on." (p.4) This definition would be inconvenient were it not for the fact that we are interested only in costs as a function of cumulative depletion, independent of time.

accomplished using a deflator of .67 which is based on a nondurable goods price index* of 127.7 for 1970 and 179.6 for 1975 II, which we arbitrarily extrapolate to 190 for 1976.

So far the NPC *Enhanced Oil Recovery* report has yielded only two points for oil prices at two levels of cumulative depletion. We wish to also find capital and operating costs at these levels. This is done by applying the ratios of operating cost/price and capital cost/price from 1985 (cumulative depletion = 918 quads) from the first NPC report to the two new prices. In 1985, capital costs were about 40% of price received and this was assumed to hold true at cumulative depletion levels 1070 and 1130. In 1985 operating costs were 10% of price received. However, this is before enhanced oil recovery becomes prominent in domestic operations. When production is entirely by enhanced methods, operating costs are expected to increase; we assume an operating cost figure of about 20% of price. These assumptions yield data points as follows:

Cumulative depletion quads	price received per bbl ($ 1970)	operating cost per bbl ($ 1970)	capital cost per bbl ($ 1970)
1070	10	2.2	4.0
1130	17	4.2	7.0

The final step in creating this data base is to linearly extrapolate the above two sets of points until cumulative depletion reaches 2300 quads. In this region price continues to increase at the rate determined by the above two points ($.12 per barrel per quad), and operating and capital costs remain at 22 and 40 percent of price, respectively. Table B-1 shows the entire final set of data points employed.

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* National Income and Products Account, Table 8.2. U.S. Department of Commerce, Survey of Current Business, July 1976 and July 1972.

Table B1: Complete Oil Data Base

Point	(quads) cumulative production	Operating cost ($ 1970 per bbl) [10^6 $ 1970 per quad]	Capital Cost ($ 1970 per Bbl) [10^6 $ 1970 per quad]	Price ($ 1970 Bbl)
1.	390	1.09 [188]	1.90 [328]	3.33
2.	450	NA	1.74 [300]	3.26
3.	564	.78 [134]	1.34 [231]	3.18
4.	582	.59 [102]	1.08 [186]	NA
5.	660	.63 [109]	1.73 [298]	3.65
6.	780	.56 [97]	2.00 [345]	4.90
7.	918	.64 [110]	2.53 [436]	6.69
8.	1070	2.4 [414]	4.0 [690]	10.0
9.	1120	4.2 [724]	7.0 [1207]	16.6
10.	1220	5.8 [1000]	11.2 [1931]	28.60
11.	1300	7.2 [1241]	15.2 [2620]	38.20
12.	1400	9.0 [1552]	20.0 [3448]	50.20
13.	1500	11.0 [1897]	24.8 [4276]	62.20
14.	1600	12.8 [2207]	29.2 [5034]	74.20
15.	1700	15.0 [2586]	34 [5861]	86.20
16.	1800	16.6 [2862]	39 [6724	108.20
17.	1900	19.0 [3276]	43.4 [7482]	120.20
18.	2000	21.0 [3620]	48 [8275]	132.20
19.	2100	22.6 [3896]	53 [9137]	144.20
20.	2200	24.2 [4172]	57.8 [9965]	156.20
21.	2300	25.6 [4413]	62.6 [10,792]	168.20

B3.0 INTERPOLATION AND EXTRAPOLATION

Data points listed in Table B1 have units of quads and \$/bbl. For consistency, before deriving the functions, we convert \$/barrel to million \$/quad by multiplying operating and capital costs by (172.4 million \$/quad) = $(5.8 \times 10^6$ Btu/bbl$)^{-1}$ * $(10^{15}$ btu/quad$)^{-1}$ * $(10^6$ \$/million \$$)^{-1}$. The results are shown in parentheses in table B1.

We now have a complete set of data with correct units based on a 2300 quad ultimate depletion. Next we do a simplified piecewise linear interpolation on each consecutive pair of points to generate a smooth relationship between costs and cumulative production. The 1967 cumulative production was used to determine capital and operating costs for 1967 by linearly interpolating with known capital and operating costs. Operating cost is assumed constant at \$159 million/quad (1967 cumulative production) until the cumulative depletion reaches 942 quads.* The final operating functions are defined as:

$$\begin{aligned} OC &= 159.0 && 390 \leq CP \leq 942 \\ OC &= 2.0 * CP - 1726.0 && 942 \leq CP \leq 1070 \\ OC &= 3.25 * CP - 3064.8 && 1070 \leq CP \leq 2300 \end{aligned}$$

where OC = operating cost (million \$/quad)

CP = cumulative production (quads)

Similarly, the capital cost is assumed constant at 243 million \$/quad until cumulative production reaches 722 quads. After determining equations for the other lines, the capital cost function becomes:

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* For simplicity, we assume no decline in the real costs of crude oil extraction even though historical and projected data in the decade after 1967 show some decline in per-barrel dollar costs we therefore hold real costs constant at the 1967 level until the data again shows them reaching 1967 levels, which occurs at a cumulative depletion of 942 quads.

$$CC = 243 \qquad 390 \le CP \le 722$$

$$CC = .392 * CP - 39.5 \qquad 722 \le CP \le 780$$

$$CC = .659 * CP - 169.3 \qquad 780 \le CP \le 918$$

$$CC = 1.67 * CP - 1098.0 \qquad 918 \le CP \le 1070$$

$$CC = 8.21 * CP - 8097.9 \qquad 1070 \le CP \le 2300$$

where CC = capital cost (million $/quad)

CP = cumulative production (quads)

B4.0 DIRECT ENERGY COST FUNCTION EOP

In addition to the general operating and capital cost functions derived above, we used an energy operating function called EOP to update $A_{crude,crude}$. This is also a function of cumulative production and was determined as follows. According to projections from Goeller (1977), the crude direct requirements of crude at the synfuel point (cumulative production of 1170 quads) will be around 500,000 Btu/bbl. Our 1967 estimate of this figure is .00187 Btu/Btu* or (dividing by 5.8×10^6 Btu/bbl) 10,846 Btu/bbl. The synfuel figure is 46.1 times the 1967 figure. Hence, we designed a linear function containing the 1967 cumulative production of 485 quads with an EOP value of 1.0 and the synfuels cumulative production of 1170 quads with an EOP value of 46.1. The equation of this line is

$$EOP = .075 * CP - 41.41 \qquad 576 \le CP \le 1170$$

where

EOP = energy operating cost (million $/quad)

CP = cumulative production (quads)

For cumulative production greater than 1170 quads, another EOP function was used. Section B2.0 describes the derivation of a line with slope

* See Appendix A for derivation of this figure.

representing percentage price increase per additional quad, cumulative depletion. This is also used as the slope of the EOP line beginning with the synfuel point (cumulative depletion of 1170 quads) where EOP has a value of 46.1. This yields:

$$EOP = .276 * CP - 276.8 \qquad 1170 \leq CP \leq 2300$$

where

EOP = energy operating cost (million $/quad)

CP = cumulative production (quads)

The EOP function is thus the combination of the two line segments outlined above.

B5.0 SUMMARY

The above operating and capital functions are those used in the all-oil economy computer program, with the resulting costs normalized so that 1967 capital and operating costs are unity.

Comparisons of the functions to published estimates of future costs show that they are reasonably accurate up to a cumulative depletion of about 1170 quads, the point at which synfuels become competitive. Estimates of tertiary oil recovery by Development Sciences, Inc. (1977) indicated that indirect production energy costs for tertiary recovery are about 25 times 1972 level. The operating cost function OP produces a much more conservative value of approximately 6 for the same quantity. DSI also states that capital costs over this period increase eight-fold, while the CAP function again uses a conservative factor of 4 increase. Similar conclusions can be drawn from a comparison with recent results from the Energy Research and Development Administration (ERDA-77-14 (1977)). Their results show that total operating energy for tertiary recovery is 37 times 1967 levels, while capital energy costs approximately double.

Appendix C: Development of the Crude and Refined Capital Vectors

C1.0 INTRODUCTION

The computer program which simulates the all-oil economy requires both the 1967 crude and refined oil industry capital vectors. These were scaled up with each iteration, reflecting the ever-increasing capital costs for both sectors. This Appendix explains the derivation of these vectors. Section C2 explains the derivation of the 1967 refined capital vector and the procedure used by the computer program to create refined capital vectors in the all-oil economy for subsequent years. Section C3 explains the derivation of the 1967 crude capital vector, which is input to the computer program. For each year that the all-oil economy is simulated, a scaling factor is determined as a function of cumulative production normalized so that the 1967 scale factor is one. The 1967 crude capital vector is multiplied by this factor and the resulting vector is the crude capital vector for that year of the simulation.

C2.0 THE REFINED CAPITAL VECTOR

There are three basic steps involved in determining this vector for 1967 and later years. First, data was collected to define a capital hardware vector for one refinery and it was converted to represent capital input per Btu of annual refinery capacity added. Next a 1967 refined capital vector was calculated using the vector just described. Finally, the last step was the creation of an all-oil refined capital vector by computer simulation.

C2.1 Data Collection and Conversion for the Refined Capital Vector

The vector listed below describes the capital (hardware, no labor) inputs required by a low-gas refinery with a capacity of 200 thousand barrels

(MB)/day taken from a study by the Bechtel Corporation (Carasso, 1976).

Sector	Sectors 1-20 are 10^3 Btu; Sectors 21-40 are 1967$
1-5	0.0
6	$2.18 * 10^8$
7	$6.0 * 10^6$
8	0.0
9	$4.0 * 10^6$
10-20	0.0
21	$6.41 * 10^4$
22	$9.0 * 10^4$
23	$1.0 * 10^4$
24	0.0
25	$1.34 * 10^5$
26	$3.2 * 10^4$
27	$1.54 * 10^5$
28	$3.51 * 10^6$
29	$9.73 * 10^6$
30	$1.59 * 10^6$
31	$1.08 * 10^8$
32	$1.53 * 10^6$
33	0.0
34	$1.75 * 10^6$
35	$9.0 * 10^4$
36	$1.06 * 10^5$
37	$1.26 * 10^7$
38	$3.19 * 10^6$
39	0.0
40	$1.72 * 10^5$

We needed to convert this vector to Btu/Btu annual capacity for the energy sectors and dollars/million Btu annual capacity for the nonenergy sectors. To do this, we divided each element of the above vector by the annual capacity of the refinery:

$$(200 \text{ MB/day}) = (200 \times 10^3 \text{ bbl/day}) * (5.8 \times 10^6 \text{ Btu/bbl})$$

$$* (365 \text{ day/year}) = .4234 * 10^{15} \text{ Btu/year}$$

The result has Btu/Btu added capacity in the energy sectors and (1967) dollars/ Btu added capacity in the nonenergy sectors. The nonenergy sectors were next multiplied by 10^6 to express them as (1967) dollars/million Btu capacity added. The result is a basic refinery capital input per unit of annual output capacity vector.

C2.2 Calculation of the Actual 1967 Refined Capital Vector

Several assumptions have been used in the calculations in sections 2.2 and 2.3. First, it was assumed that all oil used in the U.S. was domestically produced and that none was imported. Also, the assumption that crude oil energy use is equal to refined energy use since almost all crude oil goes to refineries was made. It was assumed that all refineries have an annual output of .4234 quads. Finally, a 15 year lifetime for the capital equipment, based on phone conversations with American Petroleum Institute personnel (1977) was assumed.

To determine the capital investment to the refined sector, the capital invested for replacement and the capital invested for growth were computed. The replacement capital was determined by referring back 15 years (1 lifetime) to 1952. According to the Bureau of Mines (1976), the refinery capacity added that year was .6473 quads. Hence, the 1967 replacement capital supported a refinery capacity of .6473 quads.

The refined capital required for growth was determined by calculating the average capacity added per year during the period 1963-1970. To compute this, the U.S. consumption of oil rather than U.S. production was used, since all oil consumed is assumed to be domestic.

Period	Change in crude consumption
1963 - 1964	20.6 - 20.2 = .4 quads
1964 - 1965	21.37 - 20.6 = .77 quads
1965 - 1966	22.4 - 21.37 = 1.03 quads
1966 - 1967	23.2 - 22.4 = .80 quads
1967 - 1968	24.6 - 23.2 = 1.4 quads
1968 - 1969	26.0 - 24.6 = 1.4 quads
1969 - 1970	26.8 - 24.6 = 2.2 quads
	8.0 quads total

The above figures were taken from the Bureau of Mines (1976). The average annual change in consumption over this period is 1.14 quads.

Hence, in 1967, replacement + growth gave an annual capacity added of .6473 + 1.14 = 1.79 quads (=1.79 * 10^9 million Btu). The 1967 refined capital hardware vector is the product of 1.79 * 10^9 million Btu and the vector of basic refinery capital input per unit of annual output capacity derived in 2.1. Resulting units are million Btu for the energy sectors and dollars for the non-energy sectors.

C2.3 Derivation of all-oil refined capital vectors for 1967 and following years.

As in the preceding section, refined capital added in a given year was determined from refined capacity added for growth and replacement for each year of the all-oil economy. Because replacement is very small compared to growth once the economy goes all-oil, the replacement capacity we assumed to be the same for both 1967 and later years of the all-oil economy.

In order to determine the replacement capacity needed in 1967, all-oil replacement capacity was computed:

$$(1967 \text{ not all oil replacement}) * \frac{1967 \text{ refined oil consumption}}{1967 \text{ domestic production of refined oil}}$$

$$* \frac{1967 \text{ total primary energy}}{1967 \text{ crude oil consumption}}$$

which scales up not-all-oil replacement to become all-oil replacement capacity. Since crude oil consumption is assumed equal to refined oil consumption, the calculation reduces to

$$(.6473 \text{ quads}) \left(\frac{58.3 \text{ quads}}{22.27 \text{ quads}}\right) = (.6473 \text{ quads})\ (2.62)$$
$$= 1.70 \text{ quads}$$

The 1967 all oil total primary energy of 58.3 quads was calculated using the 1967 40-order data base. The 1967 crude consumption was taken from the Bureau of Mines(1976). Hence, 1.70 quads is the constant replacement capacity used in the all-oil economy each year. The 1967 growth capacity was similarly scaled up for the all-oil economy:

$$(1.14 \text{ quads})\ (1.70) = 1.94 \text{ quads}$$

Therefore, added capacity for 1967 in the all oil economy was growth and replacement capacity, or (1.70 quads + 1.94 quads) = 3.64 quads (= $3.64 * 10^9$ million Btu).

The growth factor after 1967 can be calculated from the change in refined output, i.e., GDO_{REF} (current year) - GDO_{REF} (preceding year). So the total refinery capacity added in year t is

$$GDO_{REF}\ (t) - GDO_{REF}\ (t-1) + 1.7 \times 10^9 \text{ million Btu}$$

To determine the total investment in refined capital for year t, multiply the total refinery capacity added in year t by the investment per unit of annual output capacity derived in 2.1. The result is in Btu for the energy sectors and dollars for the nonenergy sectors. The final operation is the multiplication of the energy sectors by 10^{-6} to convert to million Btu.

C3.0 THE CRUDE OIL CAPITAL VECTOR

The derivation of the 1967 crude capital (hardware, no labor) vector is somewhat simpler than that of refined. The vector taken from Bechtel data was normalized by dividing each element by the total dollar cost (including labor costs). The 40-order vector for the capital requirements of primary on-shore oil in inputs per 1974 dollars of total capital cost is as follows:

Sector	Sectors 1-20 in 10^6 Btu/1974 \$; 21-40 in 1967 \$/1974 \$
1-5	0.0
6	.01098
7-20	0.0
21	.000392
22	.000588
23	0.0
24	0.0
25	.000784
26	.021176
27	.001176
28	.012941
29	.073922
30	.001176
31	.176863
32	.016471
33	0.0
34	.009804

35	.000588
36	0.0
37	.049216
38	.022941
39	0.0
40	.001373

To convert 1974 dollars to 1970 dollars in the denominator, for the next step each element of the above vector was multiplied by the ratio of the 1974 capital cost index to the 1970 capital cost index found in several issues of the Engineering News Record.

$$\frac{\text{1974 capital cost index}}{\text{1970 capital cost}} = \frac{2095.3}{1368.66}$$

$$= 1.5309$$

The resulting vector is in million Btu/1970$ in the energy sectors and in 1967$/1970$ for the nonenergy sectors.

The total investment in crude capital for 1967 in 1967 dollars was calculated, then multiplied by the vector listed above. The resulting product was the 1967 capital investment in the crude oil sector. To calculate the total investment, first the total 1967 oil production was converted from $3.05 * 10^9$ bbl (from NPC data) to $17.69 * 10^{15}$ Btu by multiplying by $5.8 * 10^6$ Btu/bbl. Similarly, the 1967 cumulative oil production was converted from $80.603 * 10^9$ bbl to $467.5 * 10^{15}$ Btu. Since cumulative production was 467.5 quads in 1967, when the capital cost function was evaluated at that point, the result was 328 million dollars/quad (see appendix B). Next the total 1967 capital investment in 1970 dollars was calculated by multi-

plying the cost of 328 million dollars/quad by the 1967 oil production, 17.69 quads, for a result of $5802.32 * 10^6$ (1970) dollars invested in crude capital in 1967.

The results this far are the total 1970 dollars invested in crude capital in 1967 and a vector of energy and nonenergy crude capital inputs per 1970 dollars. The product of these two is the energy (million Btu) and non-energy (1967$) crude capital inputs. The final step is to scale up the vector for the all oil scenario by multiplying each element by

$$\frac{\text{1967 total primary energy}}{\text{1967 crude consumption}} = \frac{\text{58.3 quads}}{\text{23.57 quads}}$$

$$= 2.47$$

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